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Asian Eocene monsoons as revealed by leaf architectural signatures

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ABSTRACT

The onset and development of the Asian monsoon systems is a topic that has attracted considerable research effort but proxy data limitations, coupled with a diversity of definitions and metrics characterizing monsoon phenomena, have generated much debate. Failure of geological proxies to yield metrics capable of distinguishing between rainfall seasonality induced by migrations of the Inter-tropical Convergence Zone (ITCZ) from that attributable to topographically modified seasonal pressure reversals has frustrated attempts to understand mechanisms underpinning monsoon development and dynamics. Here we circumvent the use of such single climate parameter metrics in favor of detecting directly the distinctive attributes of different monsoon regimes encoded in leaf fossils. Leaf form adapts to the prevailing climate, particularly under the extreme seasonal stresses imposed by monsoons, so it is likely that fossil leaves carry a unique signature of past monsoon regimes. Leaf form trait spectra obtained from fossils from Eocene basins in southern China were compared with those seen in modern leaves growing under known climate regimes. The fossil leaf trait spectra, including those derived from previously published fossil floras from northwestern India, were most similar to those found in vegetation exposed to the modern Indonesia–Australia Monsoon (I–AM), which is largely a product of seasonal migrations of the ITCZ. The presence of this distinctive leaf physiognomic signature suggests that although a monsoon climate existed in Eocene time across southern Asia the characteristics of the modern topographically-enhanced South Asia Monsoon had yet to develop. By the Eocene leaves in South Asia had become well adapted to an I–AM type regime across many taxa and points to the existence of a pervasive monsoon climate prior to the Eocene. No fossil trait spectra typical of exposure to the modern East Asia monsoon were seen, suggesting the effects of this system in southern China were a much later development.

1. Introduction

An annual reversal of surface winds underpins the basic definition of a monsoon (Ramage, 1971), but associated with such reversals are strong variations in rainfall (Wang and Ding, 2006). A global monsoon network arises from seasonal latitudinal excursions of the Inter-tropical Convergence Zone (ITCZ) (Webster and Fasullo, 2003) and in an ocean covered world the ITCZ monsoon would be global and straddle the equator. However, in reality this zonal pattern is disrupted, and in places amplified, by continental configuration and topography, no more so than in the case of the modern Asia monsoon systems.

The monsoon systems affecting Asia are divisible into the South Asia Monsoon (SAM), characterized by dry winters and wet summers with temperatures peaking in May/early June just before the sudden onset of the rainy season, and the East Asia Monsoon (EAM) (Molnar et al., 2010). The EAM is typified by a cold and dry winter that penetrates deeply across eastern Asia under the influence of air masses from the Siberian High, followed by heavy rain in late spring to early summer as a low pressure cell develops over the warming Siberia and allows moist air to penetrate from the south (Molnar et al., 2010). The mechanisms underpinning the EAM are clearly different from those of the SAM, which is strongly influenced by topography but in ways that are poorly understood (Boos and Kuang, 2010; Molnar et al., 2010). The characteristics of

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the EAM are so unusual that some authors question if it should be regarded as a monsoon at all (Molnar et al., 2010). The SAM is most strongly felt over northern India and the northeastern Indian Ocean, while the EAM most strongly affects China, the Korean Peninsula, and southern Japan. In parts of southern China these systems interact and Yunnan, Guangxi and Guangdong provinces experience a complex climate regime with considerable inter- and intra-annual variation (Wang and Ho, 2002).

Several other monsoon systems are commonly recognized outside of mainland Asia. Here we consider just two of them: the Indonesian–Australian Monsoon (I–AM) and the North American Monsoon (NAmM). The I–AM extends across parts of northern Australia to the south of the Indonesian main islands, e.g. Sumatra and Kalimantan. It is largely zonal and controlled by the migrations of the ITCZ. Because equatorial Indonesia experiences year-round high rainfall the seasonal contrasts in precipitation are muted and Indonesia is normally excluded from the region considered monsoonal (Zhang and Wang, 2008). In contrast to the humid I–AM the NAmM is experienced over a broad expanse of predominantly arid southwestern North America, encompassing much of the western United States and northwestern Mexico (Adams and Comrie, 1997).

Changes in Asian monsoon systems (including both SAM and EAM) over evolutionary timescales are poorly understood, as are the causes of these changes. Numerous studies have attempted to reconstruct the evolutionary history of Asian monsoon circulation (e.g. An et al., 2001; Passey et al., 2009; Wan et al., 2007) but because the drivers of the Asian monsoon systems are complex (e.g. Boos and Kuang, 2010; Molnar et al., 2010) and because there is no commonly applicable simple proxy to measure monsoon characteristics over evolutionary timescales, the developmental history of the Asian monsoon systems remains controversial and largely obscure. Indices to investigate short-term temporal changes in monsoon intensity have been based on either climatic parameters (e.g. Liu and Yin, 2002; Parthasarathy et al., 1992; Zhang and Wang, 2008; Zhao et al., 2009), or atmospheric circulation (e.g. Goswami et al., 1999; Wang and Fan, 1999), but these are not applicable to the geological record. For deep time monsoon development studies far less precise proxies such as those based on loess-paleosol successions, isotopic data (e.g. Licht et al., 2014), and terrestrial fossil records, usually translated via a variety of transfer functions into rainfall seasonality, have to be used (e.g. Shukla et al., 2014; Srivastava et al., 2012; West et al., 2015; Xing et al., 2012). Consequently the individual monsoon systems are hard to differentiate from each other and their origin and development are difficult to document.

Fundamental to understanding the history of monsoon dynamics is the ability to distinguish climate phenomena arising from ITCZ migration from those influenced by topography. In the context of the geological record metrics incorporating the ratio of wet to dry season rainfall are commonly used as indices of monsoon intensity (e.g. Jacques et al., 2014; Shukla et al., 2014; Spicer et al., 2014; West et al., 2015). However, rainfall patterns are strongly influenced by factors other than those associated with monsoon circulation, particularly at low latitudes such as in southern China. Here any changes in the seasonal latitudinal migration of the ITCZ, driven, for example, by changes in the latitudinal temperature gradient (e.g. Hasegawa et al., 2012), will affect the seasonal wet/dry precipitation ratio experienced at any given location. Indices that rely on such ratios must therefore be used with caution in low latitudes, making it particularly difficult to detect the onset, or changes in intensity, of topographically-modified monsoon circulation: a critical issue in understanding the drivers of the Asian monsoon systems.

Another factor that can confound the use of the rainfall regime as a monsoon indicator over geological time is that most preserved sediment and associated fossils, be they animal or plant, accumulated in depositional basins. This biases the climate signal towards that obtained where water also accumulates, which inevitably moderates the local environment either directly through evaporation to the atmosphere or through hysteresis in the water supply to the organism (e.g. the soil system in the case of plants).

The Eocene is an important time in the history of Asian monsoon systems because it was only recently that the existence of an Eocene SAM was postulated (Licht et al., 2014; Shukla et al., 2014) and, although climate modeling suggests that under elevated pCO_2 a strong Eocene SAM should exist irrespective of the height and extent of the Tibetan Plateau, the EAM is unlikely to have existed at that time (Huber and Goldner, 2012). Instead of using a monsoon index based around a proxy-derived single meteorological parameter such as rainfall, here we attempt to use leaf form (physiognomy) directly to detect and 'fingerprint' Eocene monsoon influence in southern China. As far as a leaf is concerned a monsoon is more than just variations in rainfall, but rather a combination of soil moisture availability, atmospheric humidity and temperature that fluctuate markedly throughout the lifetime of that leaf, and the leaf has to possess features (traits) that allow it to function effectively under those changing conditions.

Natural selection favors leaves that have architectures well adapted (optimized) to their immediate surroundings because such well 'tuned' leaves maximize photosynthetic return while minimizing structural and maintenance costs (e.g. Bloom et al., 1985; Givnish, 1984). Architectural trait spectra, not just from individual leaves but leaf aggregates across numerous taxa of woody dicotyledonous flowering plants (dicots) within stands of natural modern vegetation, show strong correlations with the local prevailing climate (Yang et al., 2015). Leaf form encodes a variety of climate signals simultaneously spanning temperature, precipitation and atmospheric moisture.

Southern China is particularly interesting because not only is it an area where today the SAM and EAM interact, but it is also an area potentially subject to the effects of ITCZ seasonal migration, and modeling suggests that ITCZ migration extended further poleward in the Eocene (Huber and Goldner, 2012). By comparing leaf physiognomic trait spectra from different climates, specifically different monsoon regimes, it should be possible to determine if fossil leaves possess characteristic climate signatures in their physiognomy that would allow atmospheric phenomena driven by ITCZ seasonal migrations to be distinguished from those arising from topographic modification of the climate system.

We use this approach to address the following questions:

1. Do the leaves of woody dicots posses leaf form signatures characteristic of different monsoon regimes?
2. Were any of these present in southern China during the Eocene?
3. If they were present, which modern monsoon leaf form signatures did they most closely resemble?
4. Did these monsoon signatures show any pattern of change over time?

2. Our approach

2.1. Modern leaf samples

To answer these questions we employed the global data set of present day leaf physiognomic traits (PhysgGlobal378) presented in Yang et al. (2015). This data set consists of leaf traits from 378 vegetation sites distributed across all continents except Antarctica. As such the vegetation sites represent regions of the globe subject not only to the SAM, EAM and non-monsoonal climates, but also other monsoon regimes such as that seen in southwestern North America. At each site the full morphological range displayed by